# Use of Orthogonal Curvilinear Grids for the Representation of the Littoral Ocean Environment


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**ABSTRACT***: The effective representation of the littoral ocean environment has been a long-standing challenge for the Modeling and Simulation (M&S) community. The need for such a representation continues to grow, as the U.S. Navy refocuses from deep ocean to littoral missions. One of the greatest challenges of the littoral region is the wide range of spatial and temporal scales that must be represented. For example, the cross-shore gradients of important oceanographic parameters are typically an order of magnitude larger than the along-shore gradients. Unfortunately, the representation techniques typically employed by the real-time M&S community are not well suited to this extreme range of scales. These representations have included regular Cartesian and geodetic grids, as supported by the IEEE 1278.1a-1998 Gridded Data protocol. This paper describes the application of grids based on an orthogonal curvilinear system to the littoral environment. Orthogonal curvilinear grids were originally developed by the computational fluid dynamics community to improve the simulation of fluid flow. Such grids are now routinely used in numerical models of the littoral ocean environment. They allow a wide range of spatial scales while preserving key boundaries and maintaining some of the traditional advantages of gridded representations. One of the distinctive advantages of the use of an orthogonal curvilinear grid systems is the economy of computational and storage resources that can be attained. Methods for generating operational grids and practical aspects of employing them in the STOW Synthetic Natural Environment are discussed.*


## 1. Background:

With the end of the Cold War, the focus of U. S. Naval strategy has shifted to littoral regions [1]. Littoral regions are those "near" a coastline. From a military perspective, the littoral ocean includes the area from which naval forces may engage or otherwise influences forces or actions on shore. From an oceanographic perspective, the littoral ocean includes waters on the continental shelf and in adjacent seas excluding estuaries. While a good understanding of the deep ocean environment was developed during the cold war,

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capturing the important phenomenology in the littorals remains a challenge. One of the greatest challenges in representing the littoral ocean environment for modeling and simulation is the extremely wide range of spatial scales required. This paper describes a representation that effectively deals with this wide range of spatial scales. This representation is based on orthogonal curvilinear grids. These grids are applicable both to the generation of littoral ocean data using numerical ocean models, and to the use of the output of such models in military modeling and simulation.

### 1.1 Physical Basis of the Wide Range of Spatial Scales in the Littoral Ocean

The littoral, or coastal, ocean exhibits a great degree of variations of oceanographic parameters compared to the deep ocean environment. The most notable examples are the spatial and temporal variations in currents and in the temperature and salinity, and hence density, of seawater. Factors accounting for these variations are the coast as a boundary to ocean currents, the shallow water depth over the continental shelf, freshwater inflows from rivers and rainfall, and the influence of atmospheric forcing as weather moves from continent to coastal waters and vice versa. Many observations and studies in the littoral zone confirm the existence of a fundamental length scale, which characterizes littoral ocean processes. It is called a baroclinic radius of deformation. Both coastal upwelling and trapped waves are constrained to exist within a few radii of the coast and a few radii also typify cross-front length scales. The baroclinic radius in most of the littoral zone in mid latitudes is of the order of 20 km.

Naturally, the coast imposes a boundary to ocean circulation and hence the ocean currents tend to flow along the coastline. It is also often found that the currents tend to follow the bathymetry so that the alongshore currents are much stronger than cross-shore currents in the littoral oceans. In shallow waters, the influx of solar energy can cause greater seasonal fluctuations of temperature due to limited mixing of the deep water reservoir. Therefore, the less the water depth becomes, the greater the water temperature varies due to surface heating. This surface heating is at its maximum during the summer season in temperate regions, at which time distinct surface and deep-water separation, called a thermocline, occurs in the water column. The thermocline limits the mixing of surface and bottom layer water. The sound speed in the water column is greatly affected by the water temperature more than any other parameters so that sonar operation can be hindered at or near the thermocline. Shallow water depth in the littoral zone can cause complicated circulation patterns. Approaching ocean tides, produced mainly by the gravitational forces of the moon and sun, interact with the shallow water depth and the coast. A tidal wave will change direction and magnitude upon approaching the littoral zone due to friction at the bottom of the water column and the shape of the coastline. Hence the shallow water depth often creates much stronger tidal currents than occur in the deep ocean. Shallow water depth also triggers the breaking of wind induced surface waves at the shore.

Freshwater inflow from rivers reduces the salinity of the surface layers of water column. With sufficient vertical mixing, this reduced salinity can penetrate into relatively deep water. The salinity gradients create horizontal and vertical gradients of seawater density near the region where the freshwater sources enter the littoral zone. These horizontal and vertical gradients in turn generate density currents, or gravitational currents. The rates of freshwater inflows can occur with significant seasonal variation so that the temporal variation of salinity in the littoral ocean is much greater than that of open ocean. Riverine inflow may also carry a significant amount of sediment load into the littoral ocean as well as nutrients. Sediment settles to bottom as the current speed decreases

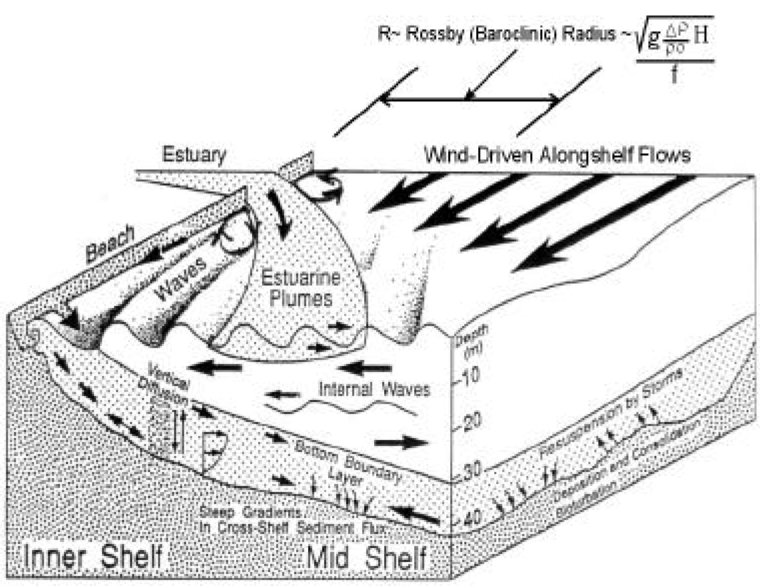


Figure 1.1 A conceptual illustration of the littoral

in open water, and can cause bottom topographic changes near the mouth of major rivers. Often fine grained sediment travels far into the open water so that the optical property of sea water changes greatly as compared to deep ocean. Another component controlling sea water opacity is the micro-organic matter in sea water. Due to upwelling of nutrient rich deep water near the continental shelf and the riverine inflows of nutrients, the littoral zone provides an optimal environment for the growth of algae and other micro-organisms. Most of fisheries in the world ocean are confined in the littoral oceans. A conceptual diagram of the processes in the littoral ocean is shown in Figure 1.1 [2].

## 2. Orthogonal Curvilinear Grids

The design of a computational grid is a very important part of modeling. One must choose the proper resolution of modeling grid in order to account for spatial variation of the parameters to be considered. One of the greatest challenges of the littoral region is the wide range of spatial and temporal scales that must be represented. For example, the cross-shore gradients of important oceanographic parameters are typically an order of magnitude larger than the along-shore gradients. Unfortunately, the representation techniques typically employed by the real-time M&S community are not well suited to this extreme range of scales. These representations have included regular Cartesian and geodetic grids, as supported by the IEEE 1278.1a-1998 Gridded Data protocol. Orthogonal curvilinear grids were originally developed by the computational fluid dynamics community to improve the simulation of fluid flow. Such grids are now routinely used in numerical models of the littoral ocean environment. They allow a wide range of spatial scales while preserving key boundaries and maintaining some of the traditional advantages of gridded representations. One of the distinctive advantages of the use of an orthogonal curvilinear grid systems is the economy of computational and storage resources that can be attained.

An orthogonal curvilinear coordinate system permits the design of a grid system in a complicated region such as that bounded by a shoreline. The transformation between a complicated and curving grid to a rectangular grid can be described mathematically. Thus, by incorporating the grid transformation into the equations of motion describing the flow physics, the numerical computation can be thought of as occurring across a rectangular or Cartesian coordinate, computational grid. The irregularities of the physical grid are represented by "mapping coefficients" which describe the transformation between the physical and the computational grids.

An orthogonal curvilinear grid system preserves right angles between the two coordinates at every point of interest in the grid. The region bounded by two adjacent segments of one of the curvilinear coordinates and two adjacent segments of the other curvilinear coordinates will be transformable to a rectangle [3]. A straightforward example is the annular region between two concentric circles where one of the curvilinear coordinates is a radius and the other curvilinear coordinate is made up of a concentric circle placed at a constant radius in the annular region (Figure 2.1). The grid is determined by placing several radii at various angles around the circle and likewise placing more concentric circles at various radii in the annular region.

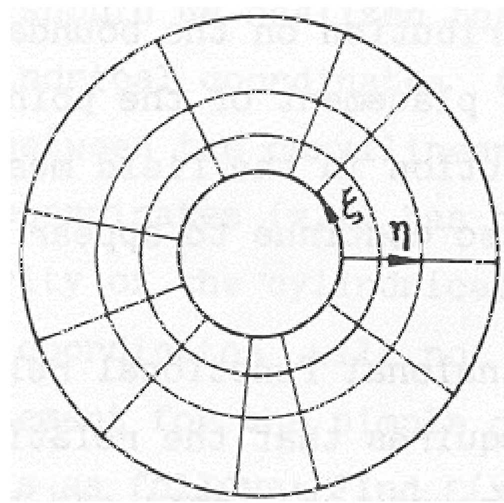

Figure 2.1. The conformal mapping of annular rings: η denotes the grid dimension along the circumference of the rings and ξ for the radial direction.

For the above example the mathematical transformation between the physical grid in the annular region and the computational grid represented by a rectangle, may be obtained analytically. In general, the mapping coefficients for the irregular boundaries of the littoral zone must be computed numerically. Grid generation is the numerical computation of the mapping coefficients. In practice there are several methods of computing the mapping coefficients, but one of the most popular is conformal, or angle-preserving, mapping. In this method the boundary coordinates are repeatedly subjected to a conformal mapping which maps the each separate segment to a straight line, except for points at grid corners. The points at grid corners are mapped to right angles. Once the boundary points have been distributed, a Laplace equation solver can fill in the interior of the domain containing orthogonal grid lines [4].

## 3. Examples of Application of Orthogonal Curvilinear Grid System In Littoral Ocean Modeling:

An example of orthogonal curvilinear grid applied in New York Harbor and New York Bight is shown in Figure 3.1. The modeling domain covers the New York Bight from Cape May, New Jersey to Nantucket Island Shoals off the coast of Massachusetts, and most of the inland water bodies including Block Island Sound, Long Island Sound, New York Harbor and its tributaries [5]. The domain of the Hudson River extends to the dam at Troy, New York. The open boundary follows the 100 m isobath along the continental shelf break. The resolution of horizontal grid varies from 100 m in the rivers to about 50 km in the New York Bight. The grid consists of

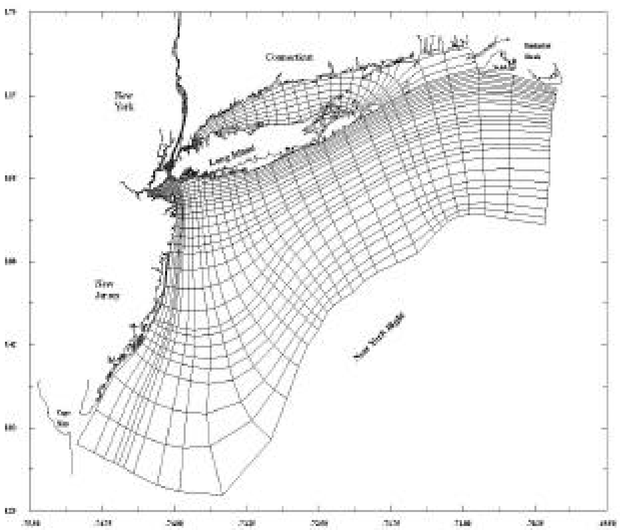

Figure 3.1. The grid of the New York Harbor region.

49 by 84 segments in the horizontal direction. By employing the orthogonal curvilinear coordinate grid, the model grid has fine resolution in the region of high variability and coarse resolution in the areas of less variability at the same time. The computational grid representation of the New York Bight model is shown in Figure 3.2. Notice how the various elements of the system are connected.

An example of orthogonal curvilinear grid for Mamala Bay, Hawaii is shown in Figure 3.3. A whole island hydrodynamic model is constructed with increased grid refinement toward the coast of the Island of Oahu. The grid consists of 27 by 83 segments in the horizontal directions. The grid cells in the vicinity of the coast are of the order of 200 m to 300 m in the cross shelf direction and, along the oceanic boundaries of the domain, the resolution increases into the range of 2 km to 4 km. The offshore extent of the modeled domain extends out to roughly the 500 m isobath.

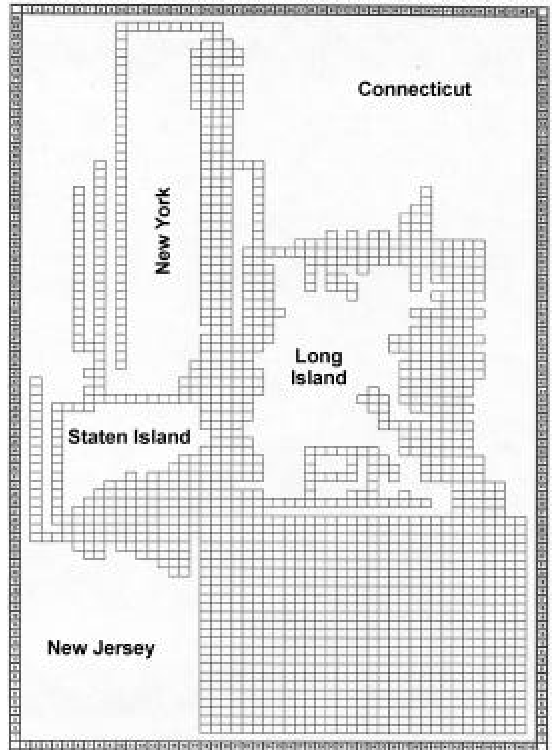


Figure 3.2. The computational version of the New York Harbor grid.

The final example presented here of an orthogonal curvilinear grid is shown in Figure 3.4 [6] and [7]. The curvilinear grid covers Massachusetts Bay with horizontal dimension of 68 by 68. The horizontal spacing ranges from 600 m in the vicinity of Boston Harbor to as large as 6 km along the open boundary in the eastern side of the grid.

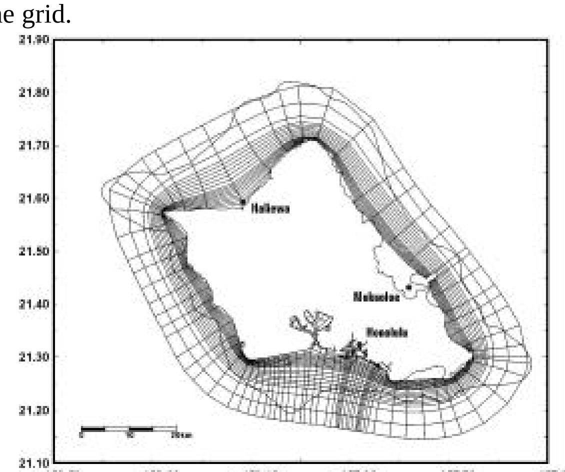


Figure 3.3. The Oahu Island grid.

## 4. Employing Orthogonal Curvilinear Grids in Military Modeling and Simulation

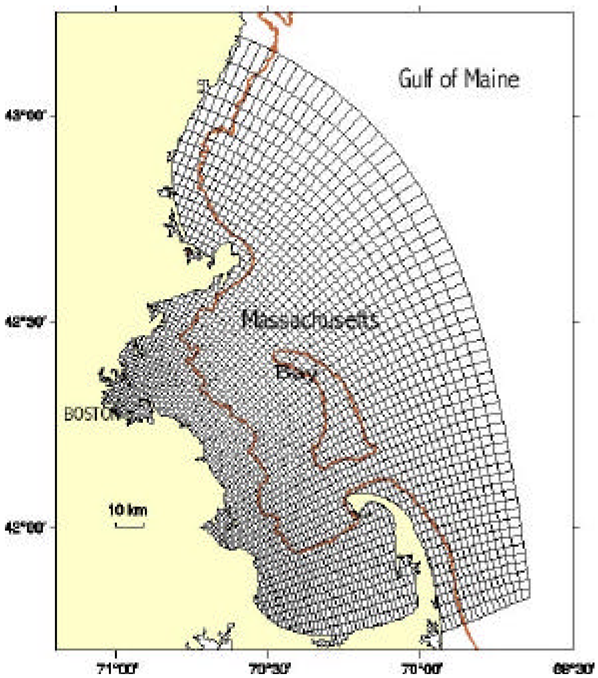


Figure 3.4. The grid of Massachusetts Bay

In order to test the utility of orthogonal curvilinear grids for military modeling and simulation, a representative application was required. JointSAF is a Computer Generated Forces (CGF) system developed by the DARPA Synthetic Theater of War (STOW) program[8, 9]. JointSAF builds on the U.S. Army's widely used ModSAF CGF system [10]. JointSAF was selected for this test because it is widely used, easy to modify, and is being increasingly employed in Naval exercises and simulations. These have included Joint Countermine Operational Simulation (JCOS) exercises and recent and upcoming Fleet Battle Experiments.

### 4.1 Implementation Approach

Figure 4.1 represents a quad tree laid on top of a curvilinear grid. The quad tree is used to find a good starting point for the traversal that will find the four enclosing points in the curvilinear grid. The circles represent the initial starting point and the query point. The arrows indicate the path of the traversal. In general quad tree nodes contain much less data than is depicted here.

A significant issue encountered while using a curvilinear grid is that of getting the desired data quickly. A sensor model in JointSAF will request ocean data at a point described in a coordinate system that is native to JointSAF. The curvilinear grid does not support any coordinate system, in fact it has it’s own coordinate system implicitly defined by the grid itself. This requires a method of starting with a JointSAF specific coordinate and locating this point within the curvilinear grid.

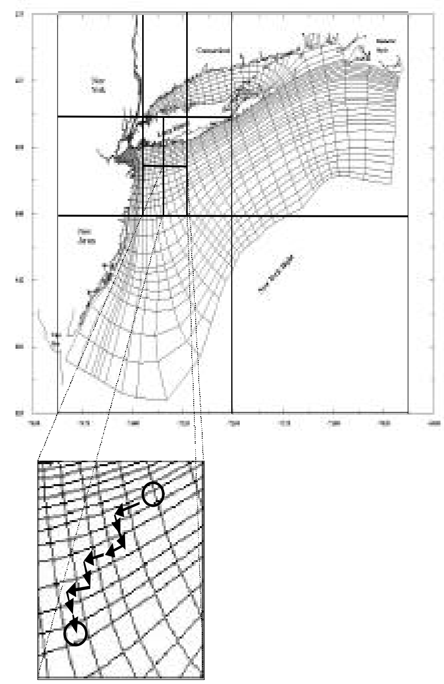

Figure 4.1. Schematic diagram representing a quad tree laid on top of a curvilinear grid.

This is a difficult task for the following reason. The curves that make up the curvilinear grid are not the result of any mathematical function. Rather they are the result of an iterative process described in [3] and [4]. If one were to solve this problem by creating a mathematical mapping that went from a JointSAF specific coordinate system to a point on a curvilinear grid, one would first have to use a curve fitting algorithm to describe the curves mathematically. The resulting function would then need to be inverted to so that a coordinate in a JointSAF coordinate system would describe a point on the grid. Given the variance in the grid curvature this could be a difficult problem to automate. It could also be computationally expensive depending on how complicated the functions that described the curvilinear grid turned out to be.

With this in mind, a high performance lookup, called a quad tree[13], was used. The curvilinear grid is fed into a quad tree, which allows rapid access to spatial data based on JointSAF specific coordinate systems. The quad tree was augmented with a traversal algorithm that will locate the four points in the curvilinear grid that bound the point being queried.

The quad tree works in the following manner. First, a coordinate system is selected that allows for easy northerly and westerly comparison of two points. In this case longitude and latitude were used. Next, as JointSAF starts up, the entire curvilinear grid is read in and inserted into the quad tree. A quad tree is much like a binary tree, differing in that a node can contain zero to three data points and that only leaf nodes contain data points. The top node of the quad tree represents the entire area covered by the curvilinear grid. The four children of the top node represent the four quadrants created by dividing the area covered by the curvilinear grid in half vertically and horizontally each node can have children by splitting the region it covers into four quadrants. A node is split into four sub nodes (representing four sub quadrants) when a fourth data point is added. Quad trees have the benefit that searches are logarithmic. Finding a point close to the point queried can be achieved quickly by making a single descent of the quad tree. Quad trees have a disadvantage in that finding the closest point to the point queried is more expensive. Finding the closest point requires descending the quad tree multiple times to verify that the close point is the closest point.

Once the quad tree finds a suitable close point to the point being queried, a traversal of the curvilinear grid is used to find the four points on the curvilinear grid that enclose the point being queried.

This method was tested using the curvilinear grid for Onslow Bay. Three separate tests were run. The first test used the quad tree to find the closest point to the query point and then begin the traversal of the curvilinear grid. The second test used the quad tree to get a close point on the curvilinear grid and use that as the starting point for the traversal. The third test started from the traversal from the middle of the curvilinear grid. The results are shown in table 1. Quad traverse indicates the number of times a the algorithm went from one node in the quad tree to another. Grid traverse indicates the number of times the algorithm went from cell in the curvilinear grid to an adjacent cell.

| Test 1 | Maximum | Average | Minimum |
|---|---|---|---|
| Time (*u*s) | 139 | 26.7 | 8.70 |
| Quad traverse | 333 | 47.3 | 17 |
| Grid traverse | 4 | 2.02 | 1 |
| Test 2 | Maximum | Average | Minimum |
| Time (*u*s) | 13.1 | 6.50 | 3.60 |
| Quad traverse | 8 | 7.08 | 1 |
| Grid traverse | 5 | 2.05 | 1 |
| Test2 | Maximum | Average | Minimum |
| Time (*u*s) | 174 | 100 | 2.00 |
| Quad traverse | 0 | 0 | 0 |
| Grid traverse | 87 | 42.7 | 1 |

Table 1

*All tests were performed on a 550 MHz Pentium III with 512k L2 cache and 256 Mbytes physical memory. As a point of comparison, access time for a Cartesian grid, which can be easily captured in a two-dimensional array, is .36 microseconds.*

The results suggest that the fastest lookup is achieved by using the quad tree to find a close point and not the closest point. By using a close point and not the closest point as the starting point for the traverse of the curvilinear traverse, the maximum and average number of quad tree traverses is greatly reduced, while the maximum and average number of curvilinear traverses increases only slightly.

This approach was integrated into the JointSAF environment architecture, which is based on a system of models and tags. Tags represent physical attributes such as temperature or current-velocity. Models can then register themselves to provide data for certain tags. The environment architecture handles queries for tags. If two models register to provide data for the same tag a resolver model is used to select the more appropriate model.

We implemented a new model, which provides ocean information from the littoral zones. The model uses the lookup described above to locate the correct points on the curvilinear grid and then access the data. The primary purpose of the model is as a proof-of-concept for the practical use of orthogonal, curvilinear grids in modeling and simulation. Consequently, we selected the most expedient method for incorporating orthogonal curvilinear grid data -- predistributed data. The data is provided in a NetCDF data file. NetCDF is a convenient, flexible and fast interface to files of the NetCDF format. The NetCDF format is designed to support array oriented scientific data. Since all the locations in the curvilinear grid have been read into memory at start up time, the NetCDF file only needs to be accessed once the four enclosing data points are located. Once the appropriate values for these data points are located, a 2D or 3D linear interpolation is performed to get the value at the query point.

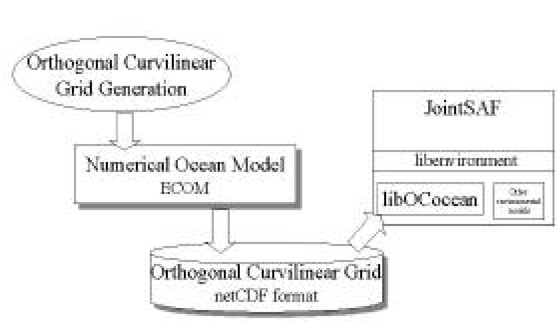


Figure 4.2. Integration of orthogonal curvilinear grids in JSAF.

The implementation within JointSAF is fast, efficient and provides data at a point from a complex source. The quad tree and traversal approach can be easily optimized to support data queries over a region as opposed to a single point.

We are using a variant of the Princeton Ocean Model as the source of our data. This ECOM (Estuarine Coastal Ocean Model) [14] model has recently added the ability to export data in NetCDF format [15]. Because of the immediate availability of orthogonal curvilinear data in NetCDF format, this format was employed in the initial model implementation. It is expected that SEDRIS interfaces will be addressed at a later stage of the program.

The implementation is being conducted in JointSAF 4.9. Because of the commonality of the underlying environmental libraries, the software should be readily integratable into similar systems (e.g., ModSAF 5.0 and JointSAF 5.0). The overall flow of data from the grid generation process, through ECOM, and its use by JointSAF is illustrated in Figure 4.2.

### 4.2 Benefits

The greatest benefit of a curvilinear orthogonal grid is the efficient use of memory and computational resources to represent a region with highly disparate spatial scales. The potential magnitude of the benefit can be seen in comparing the memory required by a curvilinear grid with that required by a uniform grid with the same maximum resolution. Table 1 provides this comparison for the Massachusetts Bay, Mamala Bay, and New York Bight grids described in Section 3. The maximum resolutions for each grid system are 0.6km, 0.25km, and 0.1km respectively. The uniform grids are taken to cover the maximum north-south and east-west extents of the curvilinear grids.

| | Uniform Grid | Curvilinear Grid | Savings w/ Curvilinear Grid |
|---|---|---|---|
| **Massachusetts Bay** | 284 x 167 | 68 x 68 | 90.25% |
| **Mamala Bay** | 280 x 360 | 27 x 83 | 97.78% |
| **New York Bight** | 5,000 x 2,400 | 49 x 84 | 99.97% |

Table 1: Grid size reduction enabled by curvilinear grids

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**PETER STEIN** is the President and Founder of Scientific Solutions, Inc. He has worked extensively in the area of underwater acoustic measurements, modeling, novel system development.

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